



Evaluation of Non-Ozone-Depleting-Chemical Cleaning Methods for Space Mechanisms Using a Vacuum Spiral Orbit Rolling Contact Tribometer

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ABSTRACT

Because CFC 113, an ozone depleting chemical (ODC), can no longer be produced, alternative bearing cleaning methods must be studied. The objective of this work was to study the effect of the new cleaning methods on lubricant lifetime using a vacuum bearing simulator (spiral orbit rolling contact tribometer). Four alternative cleaning methods were studied: ultra-violet (UV) ozone, aqueous levigated alumina slurry (ALAS), super critical fluid (SCF) CO₂, and aqueous Brulin™ 815GD. Baseline tests were done using CFC 113. Test conditions were the following: a vacuum of at least 1.3×10^{-6} Pa, 440C steel components, a rotational speed of 10 RPM, a lubricant charge of between 60-75 micrograms, a perfluoropolyalkylether lubricant (Z-25), and a load of 200N (44.6 lbs., a mean Hertzian stress of 1.5 GPa). Normalized lubricant lifetime was determined by dividing the total number of ball orbits by the amount of lubricant. The failure condition was a friction coefficient of 0.38. Post-test XPS analysis was also performed, showing slight variations in post-cleaning surface chemistry.

Statistical analysis of the resultant data was conducted and it was determined that the data sets were most directly comparable when subjected to a natural log transformation. The natural log life (NL-Life) data for each cleaning method were reasonably normally (statistically) distributed and yielded standard deviations that were not significantly different among the five cleaning methods investigated. This made comparison of their NL-Life means very straightforward using a Bonferroni multiple comparison of means procedure. This

procedure showed that the ALAS, UV-ozone and CFC 113 methods were not statistically significantly different from one another with respect to mean NL-Life. It also found that the SCF CO₂ method yielded a significantly higher mean NL-Life than the mean NL-Lives of the ALAS, UV-ozone and CFC 113 methods. It also determined that the aqueous Brulin™ 815GD method yielded a mean NL-Life that was statistically significantly higher than the mean NL-Lives of each of the other four methods.

Baseline tests using CFC 113 cleaned parts yielded a mean NL-Life 3.62 orbits/μg. ALAS and UV-ozone yielded similar mean NL-Life (3.31 orbits/μg and 3.33 orbits/μg, respectively). SCF CO₂ gave a mean NL-Life of 4.08 orbits/μg and aqueous Brulin™ 815GD data yielded the longest mean NL-Life (4.66 orbits/μg).

INTRODUCTION

Spacecraft rely on bearings to perform many operations, including attitude control, pointing, imaging, sounding, and scanning. Most of these bearings use a class of lubricants known as the perfluoropolyalkylethers (PFPAEs) (1). This lubricant class is particularly susceptible to degradation caused by changes in bearing surface chemistry (2). Degradation is affected by a variety of surface chemistries, including steel, titanium, aluminas, fluorides, chlorides, and oxides (3 to 9).

Historically, bearing preparation included several steps, some of which involved the use of CFC 113 (trifluorotrichloroethane) or 1, 1, 1-trichloroethane (TCA), both ozone depleting chemicals (ODCs).

Since the Montreal Protocol mandated that the production of these ODCs cease, new cleaning and preparation methods have to be found and validated to insure success of future spacecraft instruments. In September 1994, a workshop (10) was held to assess state-of-the-art ODC-free cleaning processes, requirements imposed by the Montreal Protocol, and the requalification status of mechanisms that had been lubricated by traditional means (heritage lubrication). It was discovered that bearing manufacturers, mechanism suppliers, and instrument fabricators had, or were about to, implement new, non-ODC cleaning processes that would negate the heritage processes used for the last 30 years. It was concluded that CFC 113 and TCA should be stockpiled to extend the use of heritage mechanisms, repeat life testing to requalify mechanisms cleaned with ODC-free solvents, and conduct generic lubricant life tests with ODC and ODC-free processes to determine if the new processes would decrease the lifetime of space mechanisms.

In 1995, a program was funded by Code AE at NASA headquarters to address the generic testing. This was a joint program with three NASA centers (Goddard, Marshall, and Glenn), Aerospace Corp., and Lockheed-Martin. An accelerated bearing test program (11) gave the first indication that ODC-free processes can affect lubricant lifetimes. In that study, a series of tests in air and using a branched PFPAE lubricant (143AC) indicated that, when compared to a CFC 113 control, two ODC-free cleaning procedures (super critical CO₂ and ultraviolet-ozone) reduced bearing lifetimes. The results are shown in Figure 1 where the means are statistically significantly different from each other at the 95% confidence level and error bars represent one standard deviation.

Other studies have shown conflicting results. Hall and Thom (12) studied adhesion performance of solid lubricants on 304 stainless steel cleaned by a variety of techniques. No difference in adhesion was observed. In accelerated gimbal bearing tests, Loewenthal et al. (13) showed that, compared to CFC 113, three ODC-free cleaning processes improved bearing lifetime. In this study another

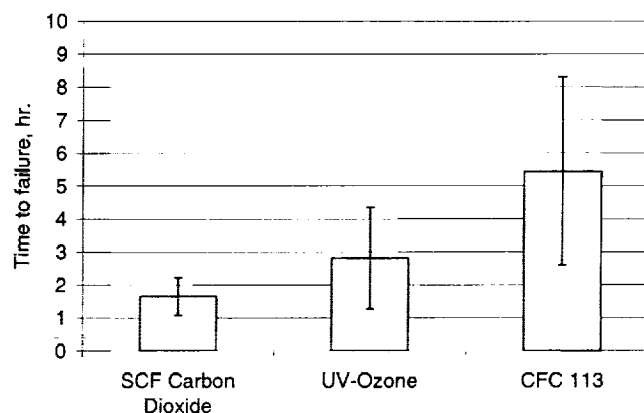


Figure 1 – Effect of ODC-free cleaners on bearing lifetimes (Parched EHL apparatus, air, 4500 RPM, room temperature, branched PFPAE (143AC)) [11]

linear PFPAE (815Z) lubricant was used. In contrast, for the same linear PFPAE (815Z), Didziulis et al. (14) showed a decrease in bearing lifetime, relative to CFC 113, for an aqueous Brulin™ cleaning process while a perfluorinated solvent (Vertrel XF) showed a small increase in lifetime. Currently, tests with a synthetic hydrocarbon (a multiply alkylated cyclopentane [MAC] 2001) and a branched PFPAE (K fluid) are continuing (15).

The spiral orbit rolling contact tribometer (SOT) used in the present study was developed at NASA Glenn Research Center. A detailed description of the functionality of the tribometer appears later in this paper. Pepper et al. (16) used the SOT facility to study the effect of various metals on the decomposition rate of a linear PFPAE (Z25). The tribometer was also used by Jones et al. (17) to study the effects of stress and ball coatings on the degradation rates of a PFPAE (143AC). Also, early work has shown a good relationship between lifetime results of actual bearings (13, 14) and relative lifetimes obtained in the SOT.

The objective of this work was to continue to study the effects of ODC-free cleaning techniques on lubricated lifetime during accelerated life tests in the boundary lubrication regime. The alternative cleaning procedures studied were ultra-violet (UV) ozone, super critical fluid (SCF) CO₂, aqueous

levigated alumina slurry (ALAS), and aqueous Brulin™ 815GD. Unfortunately, due to resource restrictions, other methods, such as the Navy Oxygen Cleaner (18) and other aqueous solvents, were not tested. Conventional CFC 113 cleaning was used as a baseline. Test specimen material was AISI 440C stainless steel. Test conditions were as follows: mean Hertzian stress 1.5 GPa, vacuum of less than 1.3×10^{-6} Pa, 10 RPM rotational speed, room temperature ($\sim 23^\circ\text{C}$), and a linear PFP AE (Z-25) lubricant.

EXPERIMENTAL

TRIBOMETER

A vacuum spiral orbit rolling contact tribometer (SOT) was used for these tests and is shown in Figure 2. The SOT is used for accelerated life testing and simulates an angular contact bearing.

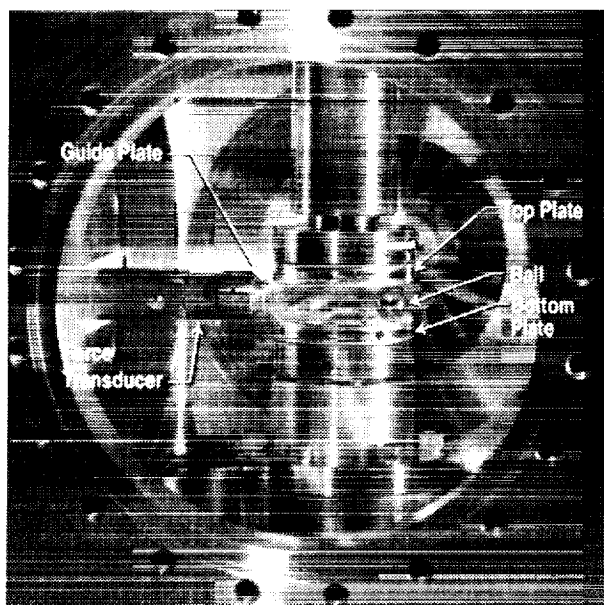


Figure 2 – The vacuum spiral orbit tribometer (SOT)

The tribometer consists of a single 12.7 mm ($\frac{1}{2}$ inch) diameter ball sandwiched between two 50.8 mm (2 inch) diameter disks, which simulate the bearing raceways, in ultrahigh vacuum. The lower disk is held fixed while the top disk is rotated. During rotation, the ball moves in a spiral orbit that is related to the frictional force between the ball and disks. A plate, called a guide plate, is used to deflect the ball back into its original orbit diameter once per

revolution. The force required to deflect the ball back into its orbit is measured and can be related to the friction force. A complete description of the tribometer can be found in Reference 19 and additional kinematic calculations in Reference 20.

Accelerated testing is achieved by using small (50-75 μg) quantities of lubricant. During the test, the lubricant is continuously consumed. This eventually results in increased friction and test failure. A typical trace of the friction force vs. ball orbits is shown in Figure 3. For these tests, a friction coefficient of 0.38 was used as the failure criteria.

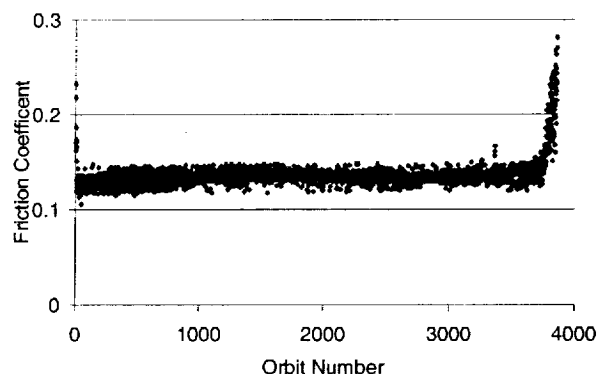


Figure 3 – Typical friction trace from the SOT

Measurements and Controls

A computer data acquisition (DAQ) and control system developed in Labview™ was used to operate the tribometer. Analog to digital conversion was done using a 12-bit computer card. The DAQ automatically initiated rotation when the vacuum level dropped below 1.3×10^{-6} Pa and terminated rotation when a 0.38 friction coefficient was reached.

MATERIALS

The ball, guide plate, and disks were made from hardened ($R_c=59$) AISI 440C stainless steel. Before each test, the guide plate and disks were polished to an average surface roughness (R_a) of 0.05 microns (2 μin). The ball was grade 25 and had a R_a of 0.05 microns (2 μin).

An unformulated, linear PFP AE (Z-25) was chosen because of its extensive use in current space mechanisms. Also, Z-25 is very susceptible to

tribochemical degradation. This yielded test times shorter than with other lubricants.

TEST PROCEDURE

Preparation, Cleaning, and Lubrication

Preparation

The disks and guide plate were polished to a R_a of 0.05 microns (2 μin) using a levigated alumina polishing compound. Then, the disks and guide plate were ultrasonically rinsed in tap water for ten minutes. The disks, guide plate, and ball were then subjected to the appropriate cleaning technique.

Lubrication

The ball was weighed dry. A dilute solution of lubricant was dripped onto the ball while it was held at a point contact and spun. The ball was placed into a vacuum system for one hour, removed, and reweighed. This method allowed for a repeatable lubricant uptake between 60-75 micrograms.

Cleaning

CFC 113

CFC 113 was used as the base line for the cleaning tests. The ball, disks, and guide plate were placed in a CFC 113 bath and ultrasonically rinsed for ten minutes and then dried with nitrogen.

Aqueous Levigated Alumina Slurry

A lint free polish cloth was moistened and coated with 0.3 μm alumina powder. The ball, disks, and guide plate were rubbed with the cloth for approximately three minutes, then rinsed with deionized water. The samples were placed in an ultrasonic bath of distilled water for ten minutes and dried with nitrogen.

UV-ozone

The ball, disks, and guide plate were sequentially placed in an ultrasonic bath for five minutes using each of the following solvents: hexane, methanol, and distilled water. They were then rinsed ultrasonically for one more minute in methanol, dried with nitrogen, and placed into the UV-ozone box for fifteen minutes (21). The ball was rotated every five minutes to ensure that the entire surface had been treated. The samples were removed, the ball was

lubricated, and the other parts placed into a vacuum system.

Super Critical Fluid (SCF) CO_2

The ball, disks, and guide plate were placed in a 200 ml SCF pressure chamber and heated to 80°C for one hour. The SCF cleaning took place under the following conditions: 225 ATM, a CO_2 flow rate of 2 ml/min, and a cycle time of thirty minutes. After the samples were allowed to cool they were removed and the ball was lubricated.

Brulin™ 815GD

A 1:20 ratio of Brulin™ 815GD to deionized water solution (22) was heated to 60°C. The ball, disks, and guide plate were ultrasonically rinsed for five minutes in the solution. Then, they were moved to a deionized water bath, also at 60°C, and ultrasonically rinsed for five more minutes. The disks were allowed to air dry and cool to room temperature and the ball lubricated.

Test Setup

Once the samples had been cleaned, the guide plate and disks were installed in the tribometer. Then, the ball was inserted so that it was touching the guide plate. This was done to ensure that the ball was always at the same diameter and there was no 'run-in' time – or revolutions that the ball did not hit the guide plate. The load was applied and the chamber evacuated.

Test

The experiment was automatically started after the vacuum level dropped below 1.3×10^{-6} Pa. All tests were performed using a mean Hertzian stress of 1.5 GPa and a top disk rotational speed of 10 RPM (rolling speed of 22.4 mm/sec). The DAQ constantly monitored guide plate force, load, pressure, revolutions, and contact resistance. The test was terminated when a coefficient of friction of 0.38 was exceeded. Normalized life was determined by dividing the number of ball orbits by the lubricant charge. For each cleaning technique, a minimum of six tests were conducted using a lubricant charge between 60 and 75 micrograms.

RESULTS

Statistical analysis was performed on the data under a natural logarithmic transformation. This transformation to NL-Life not only made the data reasonably, normally distributed, but also had the effect of making the standard deviations of the five cleaning methods not statistically significantly different from one another. This enabled a very straightforward comparison of the mean LN-Lives of the five cleaning methods. Table 1 summarizes the lifetime data. Note that the mode statistic (or "hump" of the lifetime distribution) is in original, back-transformed units (orbits/ μ g), not NL-Life. These results are shown graphically in Figure 4 in which the bar heights represent mean NL-Lives and the error bars represent \pm one NL-Life standard deviation.

Table 1 – Summary of cleaning data

Cleaning Method	Mean NL-Life	Std. Dev. NL-Life	Mode Life
CFC 113	3.62	0.19	38
ALAS	3.31	0.24	28
UV-Ozone	3.33	0.37	30
SFC CO ₂	4.08	0.22	59
815GD	4.66	0.39	106

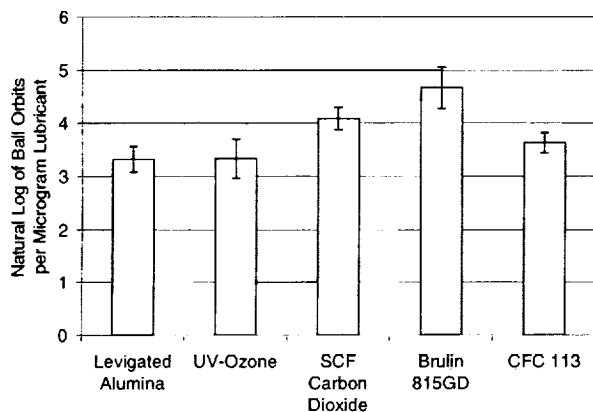


Figure 4 – Effect of various cleaning methods using the SOT (10 RPM, 1.5 GPa, room temperature, vacuum of $<1.3 \times 10^{-6}$ Pa)

To determine significant differences among the five NL-Life means, a Bonferroni (23) multiple comparison of means procedure was conducted. This procedure determined that the mean In-lives of the methods ALAS, UV-ozone and CFC 113 were not statistically significantly different from each other. Further, it found that the SCF CO₂ method yielded a

mean NL-Life that was statistically significantly higher than the mean In-lives of the ALAS, UV-ozone and CFC 113 methods, but was statistically significantly lower than the mean NL-Life of the Brulin™ 815GD method. Finally, it showed that the Brulin™ 815GD method yielded a mean NL-Life that was statistically significantly higher than the mean NL-Lives of the other four methods. All these conclusions were determined simultaneously at the 95% confidence level.

DISCUSSION

Since almost all current space systems use ODC cleaning agents during their assembly, the phasing out of these materials has been the cause of concern about long term consequences on spacecraft systems. Because new cleaning techniques may alter surface chemistry in a way to affect lubricant life, they must be investigated in order to validate their usage (1). The objective of this research was to compare lifetimes of four alternative cleaning techniques: UV-ozone, ALAS, SCF CO₂, and aqueous Brulin™ 815GD to baseline CFC 113 tests.

Discrepancies exist between these results and data gathered at NASA Glenn Research Center using a parched EHD rig. During the parched study, UV-ozone cleaning yielded a reduction in life compared with no decrease during these tests. SCF CO₂ also reduced life during the parched tests, but during the SOT tests, SCF CO₂ cleaning actually increased life compared to the CFC 113 standard (11). However, the parched tests were performed in room air using AISI 52100 steel bearings and a branched PFPAE (K-fluid), therefore the studies are not directly comparable.

Results for Brulin™ 815GD agree with preliminary results from life tests performed at Lockheed Martin (13, 14). These tests showed that Vertrel XF and Brulin™ 815GD yield longer bearing lives when compared to CFC 113. In contrast, results from Aerospace Corp. (15) showed that Brulin™ 815GD cleaning yielded lower lifetimes than the CFC 113 standard. However, Aerospace Corp.'s Vertrel data also does not correlate with the Lockheed data (13, 14).

XPS analysis of samples cleaned with the techniques used showed that the Brulin™ 815GD and SCF CO₂ cleaning techniques had a significantly greater amount of carbon left on the surface. This could represent residual hydrocarbons and account

for the higher average lifetimes by inhibiting the catalytic effect of the steel on the PFP AE. XPS data from the other cleaning methods showed approximately the same surface chemistry and correlates with their similar lifetimes.

CONCLUSIONS

Based upon these results all of the alternative cleaning methods had no effect or a positive effect on lubricated lifetimes.

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